

HINS_SS1_SOL_01 Fabrication Summary and Test Results

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I. Fabrication Summary

HINS_SS1_SOL_01 is the first prototype type1 - without correctors – solenoid, for the first superconducting section (hence the designation SS1) of the HINS linac. The design basis and evolution of the design (which is qualitatively similar to the CH section solenoids) is described in detail in a design note [1]. The solenoid was built from Main Coil (MC) serial number SS1_M01, and Bucking Coils (BC) SS1_B01 and SS1_B02.

Fabrication details are described in section III of [1]; salient features are reproduced here for convenience. The main coil of the solenoid was wound using ML-coated 0.808 mm strand (SSC B-2199); this strand was used earlier to fabricate HINS_CH_SOL_03d [2,3]. Because of the heavy coating, a packing factor of only 0.716 was reached. The estimate of the average coated strand diameter based on this experience was 0.86 mm. Oxford 0.5 mm strand is used for the bucking coils. Measured coated diameter of the strand is between 0.508 mm and 0.520 mm.

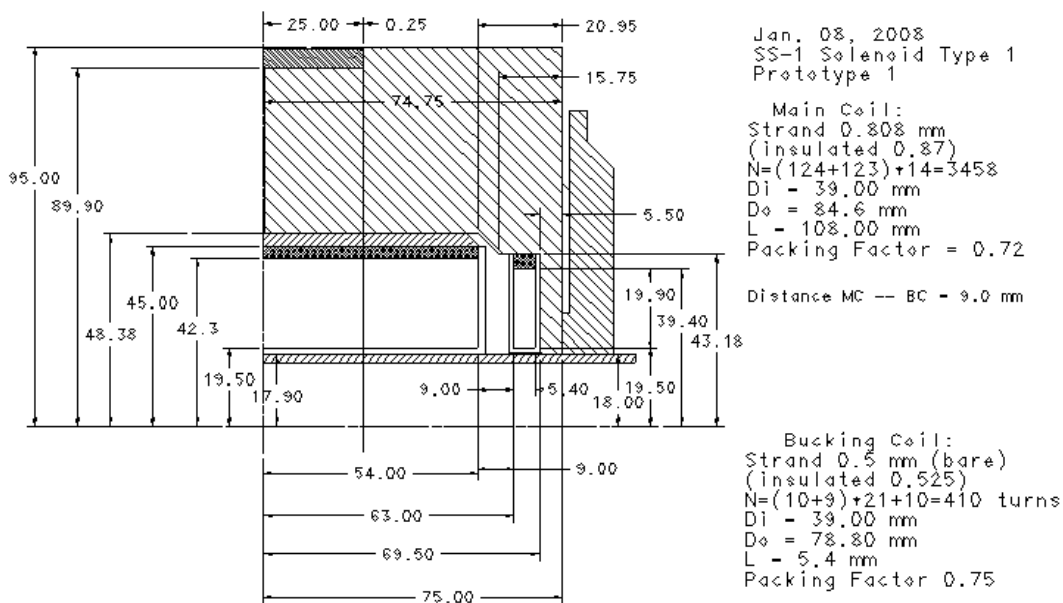


Fig. 1: SS1 prototype type 1 solenoid As-Built features

Strand critical current parameters (10^{-14} Ω -m criterion) are shown in Table 1 (0.8 mm) and Table 2 (0.5 mm) [1]. The predicted load lines and quench currents for the Main and Bucking coils are shown in Fig. 2. The load lines are based upon an Opera 2D model with as-built (300K) dimensions, with a yoke made from default non-linear soft iron BH material properties, and assumed to have a 0.2mm gap at 4.2K (0.5mm at 300K) at the center line (closed by the outer ring at 89.9mm to prevent flux leakage). The limiting quench is expected to occur in the Main Coil at a current of 220 A.

Table 1: 0.808 mm strand (SSC B-2199) critical current

B(T)	2	3	4	5	6	7	8	9
I (A)	1176	942	772	629	494	365	235	113

Table 2: 0.5 mm strand 8277-2A2B critical current

B (T)	1	2	3	4	5	6	7
Im/Ic (A)	646/618	456/453	375/367	310/307	258/254	206/201	154/149

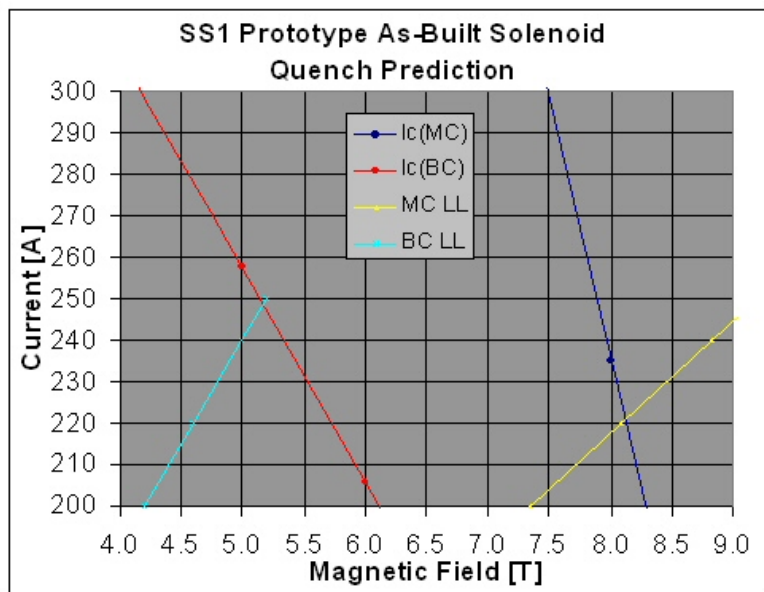


Fig. 2. Quench diagram showing peak field load lines (LL) and critical surfaces (I_c) for Main Coil (MC) and Bucking Coils (BC) in the as-built solenoid.

II. Test Overview

The first cool down took place on 3/26/08, and slow training required a second day of testing. Approximately 2.6 500-liter dewars of liquid helium were used to complete the test program. Temperature of He was within about 40mK of 4.2K during quench testing.

Significant modifications to the Test Stand 3 powering, quench protection and characterization systems were made prior to testing this solenoid. The PXI controller software was upgraded to Labview 8.5, and a new power supply control GUI was installed to allow better interactive control of the current (or use of saved ramp profiles), as well as provide the capability to control multiple power supplies (for future type 2 solenoids with correctors). Also, a new Lambda 10V, 330A power supply (PS) was commissioned in place of the previously used Lakeshore power supply units. As part of this upgrade and commissioning effort, the current readback signals were cross-calibrated against a precision shunt with a NIST-calibrated HP3458 DVM [8]. An important advantage over the previous system is that the new power supplies utilize an isolated differential input voltage drive signal, which should greatly improve stability of the power supply control by eliminating ground loops (see [4]). A number of issues and

problems were encountered during the solenoid power and quench test; the details are discussed in Appendix A.

Based upon results of a quench development model [5] and assuming the proper coil connection scheme, a new 1.5 Ohm dump resistor was procured and installed for this test. This resistance was selected to reduce the fraction of stored energy dissipated in the coil after quenching, while keeping the maximum coil voltage to ground at an acceptable level. Quench modeling shows that the coil to ground voltage depends upon the circuit, and may lead to much higher than the 500V limit to which the test subject and systems have been qualified by hi-potting. The power system and coil connection circuit overview is shown in Figure 3. Note that this power supply circuit has a symmetric grounding scheme, which was *not studied* with the quench propagation model in which the lowest voltage occurs with the MC lead connect to the dump resistor, with the dump to PS terminal held grounded [6]. Figure 4 shows a detail of the coil and voltage tap connections with labels showing the superconducting lead locations and corresponding “polarity” labels for proper field orientation

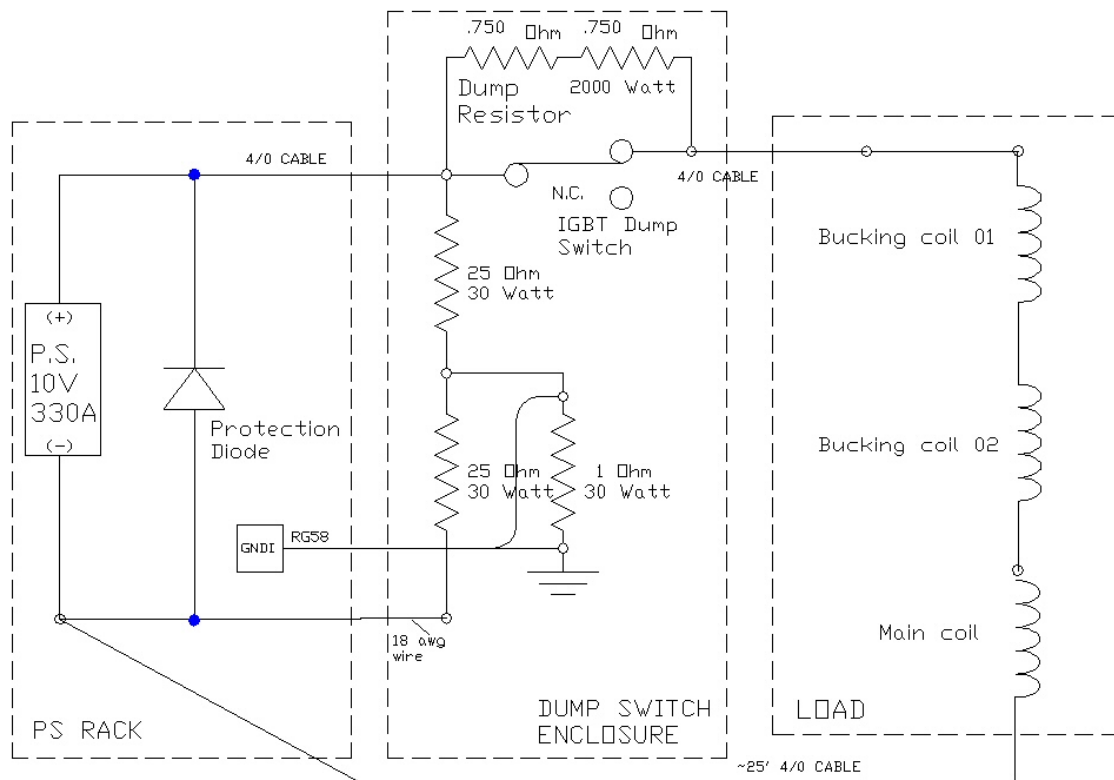


Fig. 3. Power supply circuit and coil interconnection scheme during cold test.

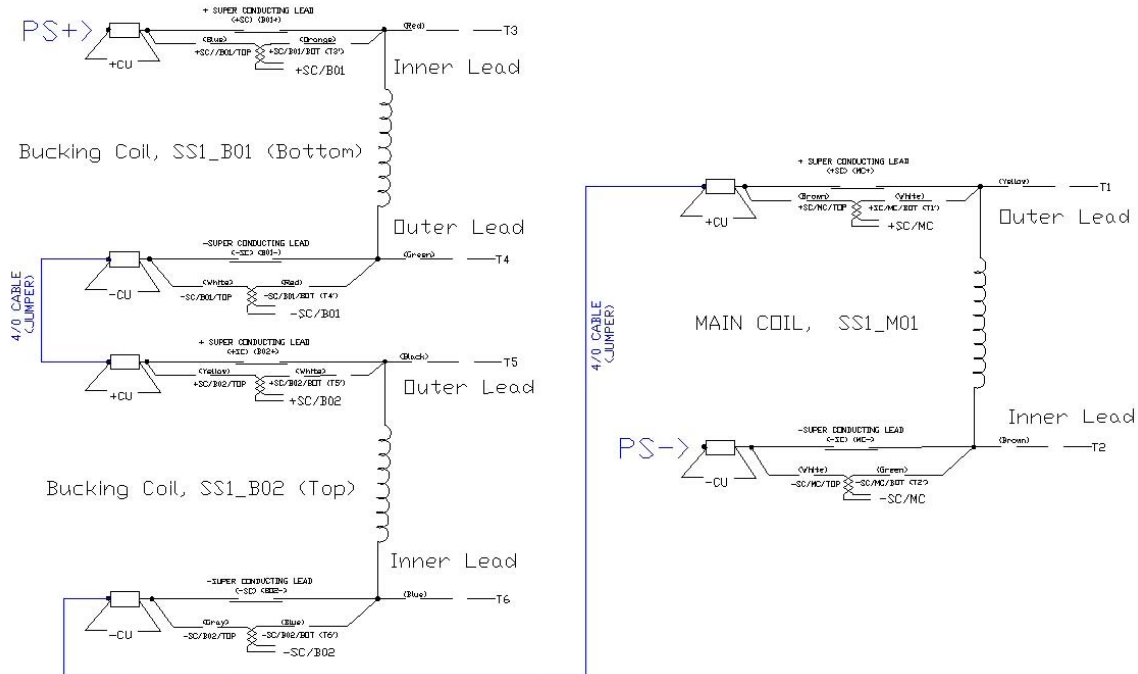


Fig. 4. Detailed Voltage Tap and Interconnection Details for HINS_SS1_SOL_01 test.

III. Quench Performance

A preliminary scan at 10A was performed prior to quench testing to check the field symmetry and to verify that BC and MC field directions were opposed, as expected. Successive training ramps to quench were timed to maintain an interval of at least 10 minutes, to allow coils to equilibrate to the bath temperature. Magnetic measurements were interspersed with quench training ramps at 1 A/s. At the end of the test, the dump resistor was removed from the circuit to test survival with no energy extraction. The quench history is shown in Figure 5 and illustrates slow but steady training in which the quench location changes between MC and BCs. Because of system problems described in Appendix A, the QC signal slightly overestimated the actual quench current. Because the current sags during quench due to power supply voltage limit, the “latched” QD quench current at detection time underestimates the actual peak current at which the quench originates; in high ramp rate cases (2, 4, 8 A/s, after ramp #25) this effect was severe, partly due to the system behavior (discussed in Appendix A) that led us to raise the WC-REF quench detection threshold close to (and even above!) the available voltage from the PS. As a result, we realized later that several of these quenches absorbed a large fraction of the solenoid energy – effectively acting as “survival tests” – including one in which the quench (ramp #35) was not detected by the system. We also found that when a quench originated in the MC at high ramp rate, the limited voltage of the power supply prevented (or substantially delayed) reaching the QD threshold, which allowed the quench to develop significantly – to the extent that both bucking coils also quenched after some delay (see Figure 6). A reasonable explanation is that the MC quench heats the helium in the vicinity of the coils and causes the BC temperatures to rise. In all of these cases, and in the explicit dump-removal test, the solenoid survived and returned to the expected plateau current level.

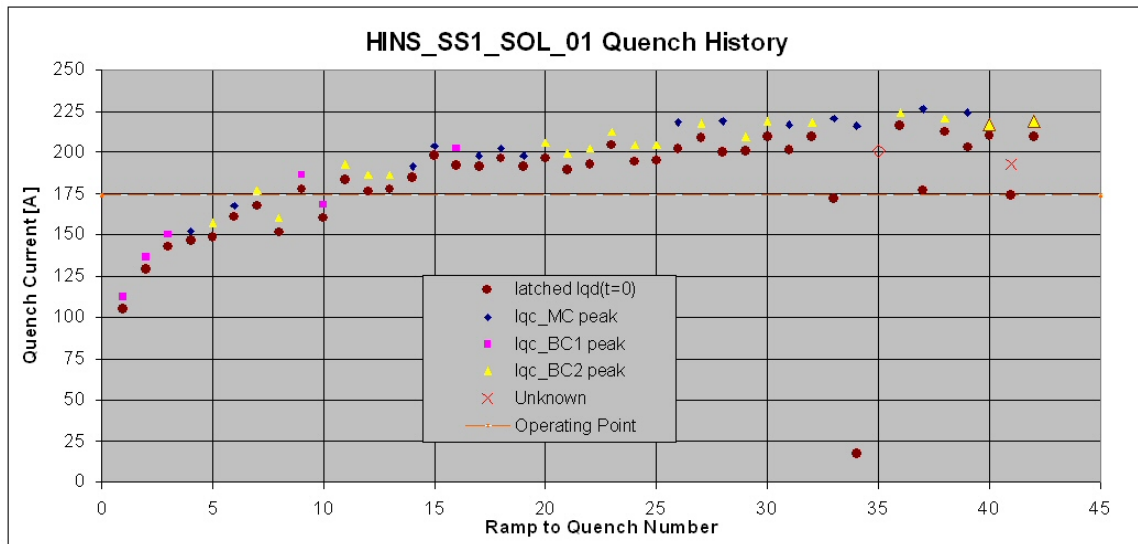


Fig. 5. Quench history of SS1 prototype solenoid; peak currents at start of quench, as reported by the “Quench Characterization” (QC) system, are shown by quench location. The QC current is systematically about 3A higher than the (calibrated and accurate) values latched at Quench Detection (QD) time, $t=0$.

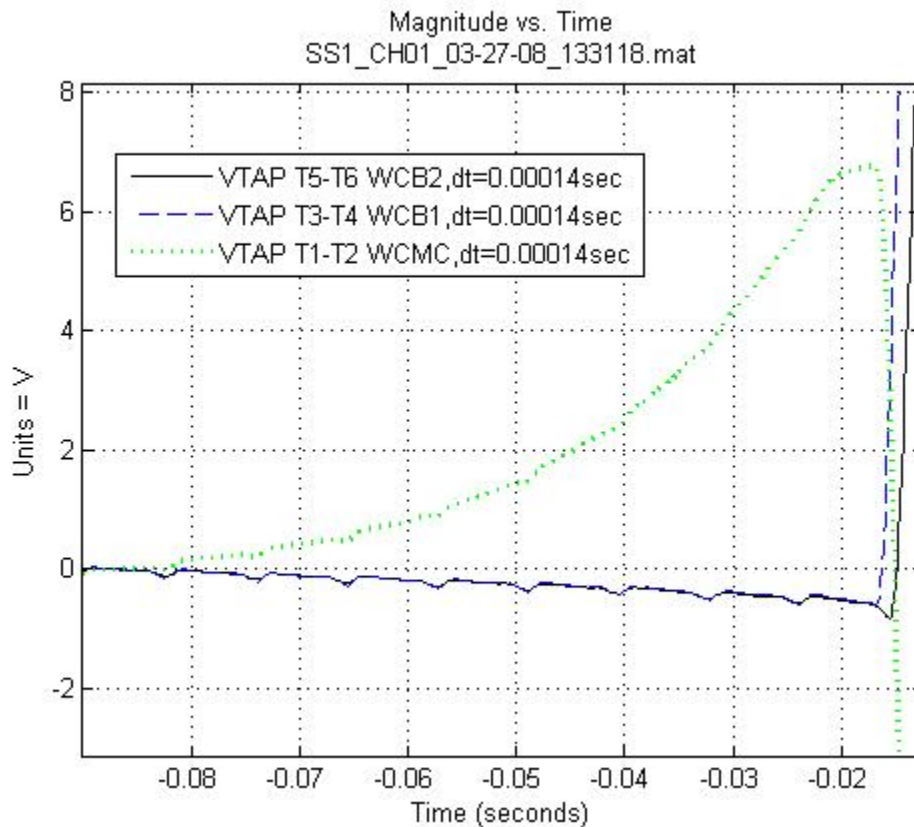


Fig. 6. Main Coil quench (#39) development during 2A/s ramp; MC voltage plateaus below QD threshold, allowing quench to continue developing until both BCs quench.

IV. Magnetic Performance

The SS1 solenoid has a smaller bore diameter than previously tested CH solenoids, and the existing warm bore does not fit the SS1 aperture. Therefore, a special G10 tube and seal was fabricated to guide a cryogenic Hall probe for magnetic measurements along the solenoid axis. We used the Cryomagnetix axial Hall probe, model HSP-A mounted in (48" long) stainless steel tubing, and the Cryomagnetix GM-700 gaussmeter to digitize the field strength. The probe position was controlled with the existing vertical drive table and measured with the existing Bausch and Lomb digitizer. These were recorded using a slightly modified version of the existing B,X,I Labview program (with Keithley 2700 DMM replaced by the Cryomagnetix instrument for acquisition of B), into which the magnet current was entered manually (and also recorded via the unix scan system). Magnetic measurements were recorded only while the solenoid was powered at constant current.

The Hall probe was zeroed prior to (but not during) the test, and the (no current) offset level was about 0.6mT everywhere, which is also the asymptotic value at large distance from the solenoid center (at high current). Magnetic measurements were intermixed with quench training ramps: We performed a precision z-scan at 190A, and a series of stair-step measurements at the solenoid center, with data taken on up and down ramps to determine the level of magnetization. The profile of field strength along the axis is shown in Figures 7 (full range) and 8 (detail of the fringe region) in comparison with prediction from the previously mentioned Opera 2D model. The agreement is good, and demonstrates that the bucking coils cancel the main coil field effectively. BC01 (below center) was built with a slightly smaller (0.3mm) outer diameter: the model indicates very little difference in the fields due to this, while data show a fairly large difference 80mm from center. Further modeling shows, in Figure 9, that this difference can be explained by slight offset in the BC position relative to MC – about 0.3mm is required to match the data. BC positioning errors on this scale are not unexpected.

Stair-step measurements at the solenoid center are illustrated in Figure 10, which shows the peak field transfer function as a function of current. The model prediction is about 2% above the measured value. (One reason for this discrepancy can be that the model used "warm" dimensions and steel magnetic properties). The measurements, most of which were taken on plateaus during up-going current ramps, show some current dependence that is reminiscent of early test solenoid experience in which magnetic material was discovered in the probe holder [7]. Coil magnetization can also lead to a similar effect, so we measured the peak field on the down-going ramp also (after peak current of 170A). The central field at 0A after the down-ramp was $B_0=3.2\text{mT}$ (versus 0.6mT for up-ramp). Figure 10 shows that this does not account for all of the change in transfer function, so there is probably some magnetic material somewhere near the probe (magnet or support).

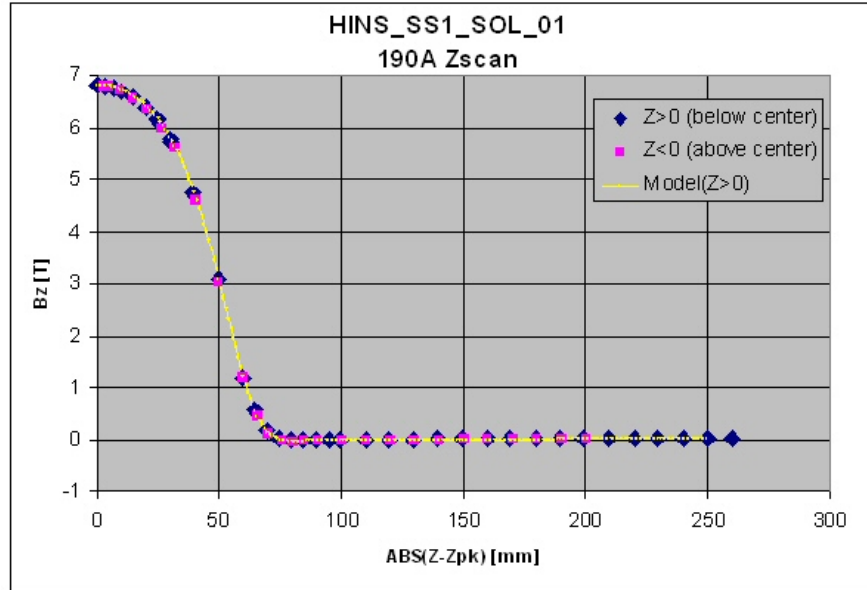


Fig. 7: Comparison of predicted and measured axial magnetic field at 190A.

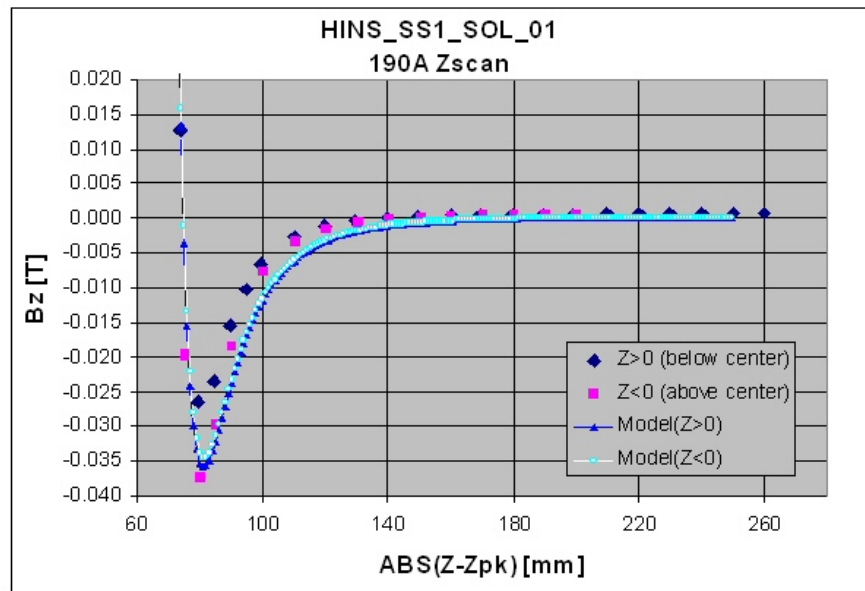


Fig. 8: Detail in fringe region of predicted and measured axial magnetic field at 190A.

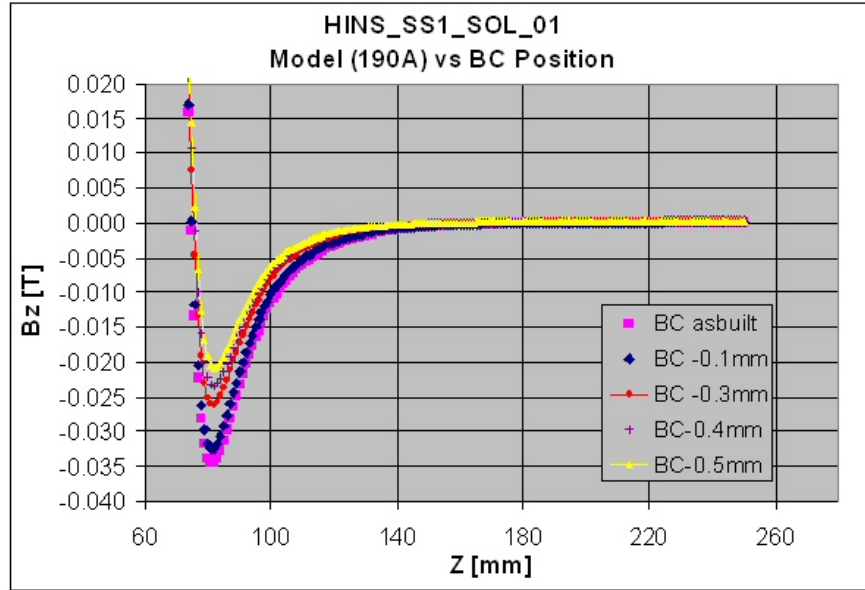


Fig. 9. Magnetic field in fringe region as position of BC is moved closer to MC.

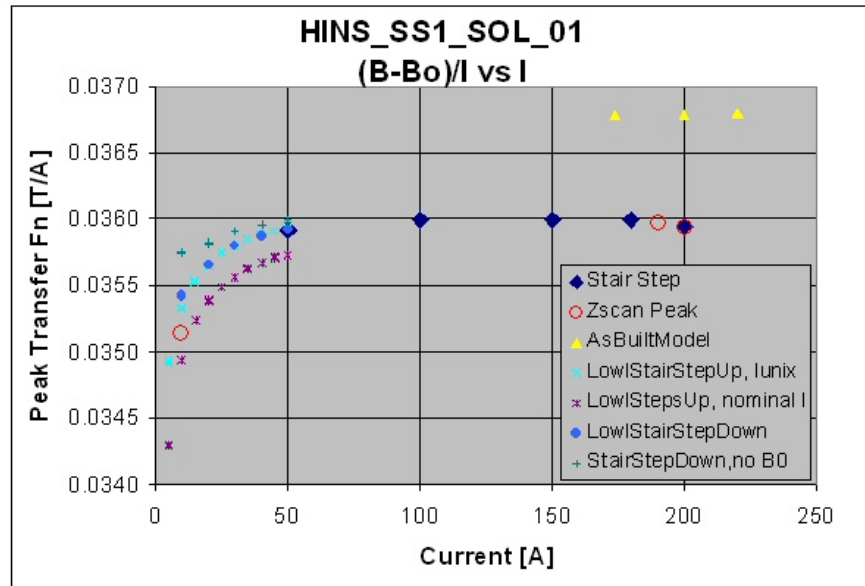


Fig. 10. Transfer function versus current with model prediction at the solenoid center

V. Conclusions

In quench performance testing the solenoid trained slowly but eventually reached a plateau at the expected MC current, with quenches occurring both in the MC and BC (which presumably would require much more training if it were possible to reach its limiting current). The solenoid was subjected to many (unexpected) “survival” quenches in which the stored energy was absorbed by the coils, and survived without degradation of the quench current.

Measurements of the axial magnetic field were made with a (previously unused) Cryomagnetics cryogenic hall probe (due to lack of a warm bore), that gave results in

good agreement with expectations, both at high field in the solenoid center and in the low field fringe regions – thus confirming the magnetic design. Some evidence for small magnetization effects and magnetic material were seen.

Future plans are to test this solenoid again when the new stand 3 helium transfer line is ready to be commissioned, and perform additional commissioning and certification of the upgraded QD/QC/PS system after following up on issues raised in Appendix A.

References

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- [2] E. Barzi, G. Davis, C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, D. Turrioni, T. Wokas, “Expected Performance and Test Results of the First Pre-Production Solenoid (Type 2, with Correctors): HINS_CH_SOL_03d,” TD-07-021, FNAL, August 2007.
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- [5] V. Veretennikov, I. Terechkine, SS-1 Focusing Solenoid Quench Protection Analysis,” TD-07-020, FNAL, August 2007
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- [7] R. Carcagno, C. Hess, F. Lewis, D. Orris, Y. Pischalnikov, R. Rabehl, M. Tartaglia, I. Terechkine, J. Tompkins, T. Wokas, “Test Solenoids Expected Performance and Test Results Part I: PDST01-0 and PDST01-1,” TD-06-027, FNAL, July 2008.
- [8] A. Makulski, F. Lewis, et al., “TS3 Current Control and Readout System Verification”, Test & Instrumentation Department Internal Document PROC-08-001Rev. No. 1, April 2008 .

Appendix A. Issues and Problems with new System Performance

Successes, issues, and problems are listed below, with recommended action items highlighted in bold font. Supporting figures follow the text.

- 1) Device name was incorrectly defined: quench files are labeled “SS1_CH01”. **A plan is being implemented to address this for production magnet testing.**
- 2) In general, the power supply control was found easy to use. The interactive control, which was utilized for most of the test, has *a scale factor of 20* in setting ramp rate parameter. **Further programming of the PS control program will be performed to correct this.** Ramp profiles help to avoid this confusion; they had been prepared in advance, but one was used for only the final ramp.
- 3) It was known before the test that there was a problem controlling the ramp with the “slider control” feature of the PS GUI, but that ramps *using programmed current profiles* did not exhibit this problem. In executing the test, the users apparently misunderstand this and continued using the “slider control” for most of the test: this resulted in large dI/dt variation and large voltage swings during the ramp, which got worse at higher ramp rates (see Figure A2). This subsequently caused the user/operator to raise the WC-REF quench detection signal threshold – which introduced problems with quench detection (discussed below, item 5). Looking at the final quench event, in which the 2A/s ramp profile was used, it is evident that the WC-REF voltage is very steady (see Figure A5), confirming good regulation was obtained with the high inductance superconducting load.
- 4) PS regulation on Flat Top was very nice (see Figure A1: at 190A, some 0.15A overshoot at start, then settles to stable <.01A plateau). The unix plateau value (after subtracting the 0.21A offset) is 189.1A, which is 0.5% low. **Further efforts to calibrate the current readout will also examine the unix values.** Regulation during ramps was confused by use of the “slider control”, but appears to be within the PS specification. The test load used for warm checkout had much smaller inductance than the solenoid, and measuring power supply performance with a similar inductance is desirable. **Plan is to utilize a different conventional magnet (one with similar inductance to the solenoid has been identified) as a test load for additional system checkout at room temperature.**
- 5) Since Whole Coil (WC) voltage was used for quench detection, and PS voltage limit was 10V (with ~3V drop across IGBT at 220A) the 4A/s quenches propagated throughout the coil and drove the current down before the (9V) threshold was reached (Figures A3, A4). At 8A/s, when Whole Coil detection threshold was raised to 12V (at 8 A/s), the quench was NOT DETECTED... power supply current dropped to 10A due to voltage limit; magnet survived and system was manually tripped off (Rcoil ~1 Ohm). **An obvious improvement would be to use Wcoil-Idot circuit for protection. (Note: the Idot signal is not being digitized and the Wcoil-Idot signal does not look sensible in QC data).**
- 6) WC-REF voltage at quench is consistently 0.5V below detection threshold. **This offset is rather large, and should be investigated.**
- 7) Because of WC voltage being limited below detection threshold, the Sc Lead circuit detected coil quenches in a number of events (quenches propagated to BC1 and BC2, then to the SC- lead) ! (Because the current was driven down by growing coil resistance in the above cases – perhaps because high ramp rate

facilitated quench propagation – the SC lead voltage did not reach threshold, Figure A6). Note that the SC- (neg.) lead signal is about 10 times smaller than SCL and SCL-WC; **this discrepancy in gain should be investigated.**

- 8) QC current signal was noisy: 3A p-p 60Hz noise (probably readout, not actual, since it persisted at 0A after quenching). Indeed, all of the QC signals show 60Hz noise on them. Investigation of current signals found QC current signal had 3 A offset (see Figures A2, A7), greater than the QD and PS readout values, and was probably caused by *a loose connection later found and fixed* in the interface box. (write-up of current readout device cross-calibration is in progress [8]). **Some additional investigation of widespread 60Hz noise should be made.**
- 9) Data were not saved for one quench event (#41), in which the system detected the quench but the quench visualization program never launched; a text file (quench header/parameters) was saved at 14:43:43, and indicates the latched quench current was 174A – somewhat below the highest value of 189 we had observed on the QD interface. It is not understood why this failed, although it had apparently occurred also during system checkout; stopping and restarting all of the labview programs was required to continue the test. **Some effort is still required to clean up and/or debug the upgraded Labview software to prevent this.**

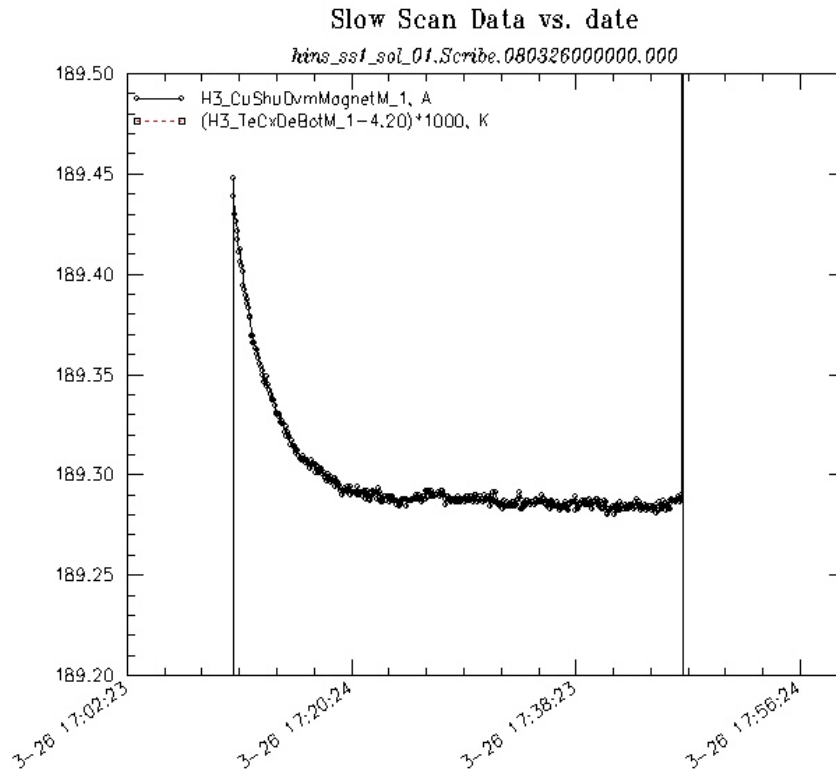


Fig. A1. Magnet current recorded by the unix scan system during 190A flat top for magnetic measurement z-scan, showing stability on plateau. The unix current readout had a 0.21A offset at zero current.

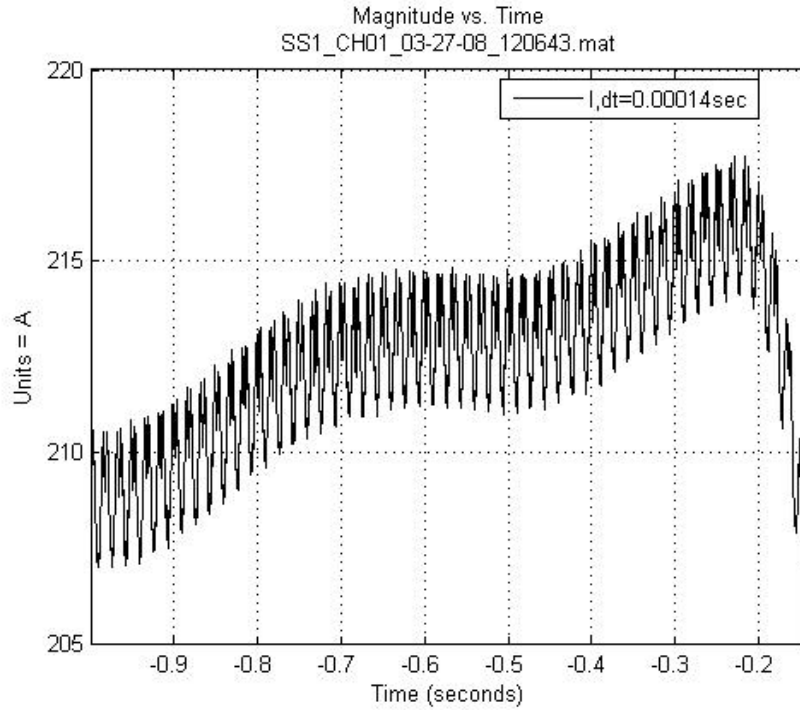


Fig. A2. Enlarged view of QC current during 4A/s ramp showing regulation (and 60Hz noise on the signal).

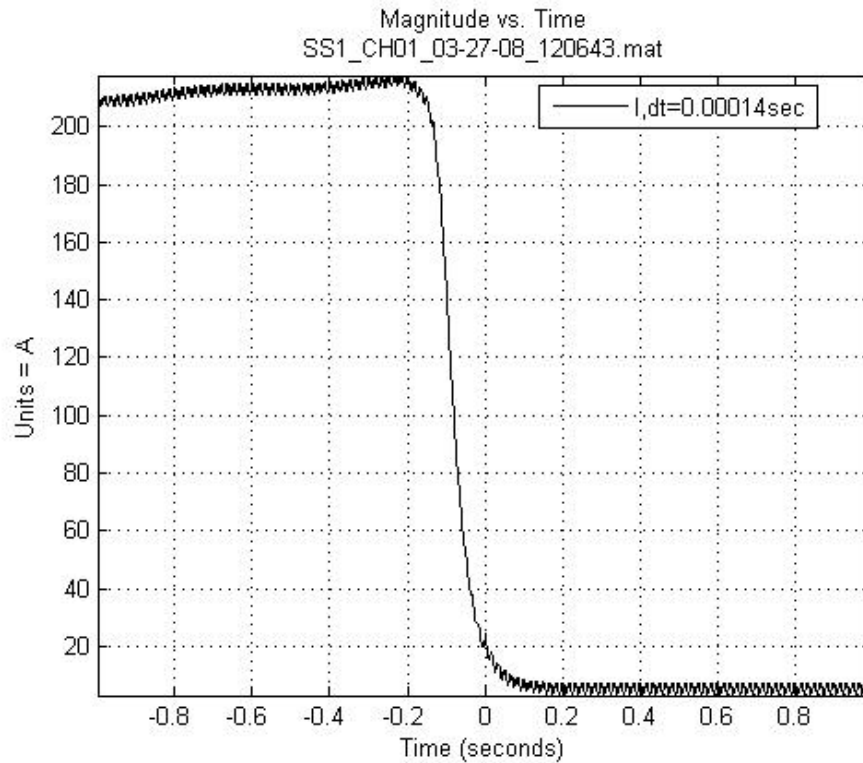


Fig. A3. Current profile during quench at 4A/s, detected long after development.

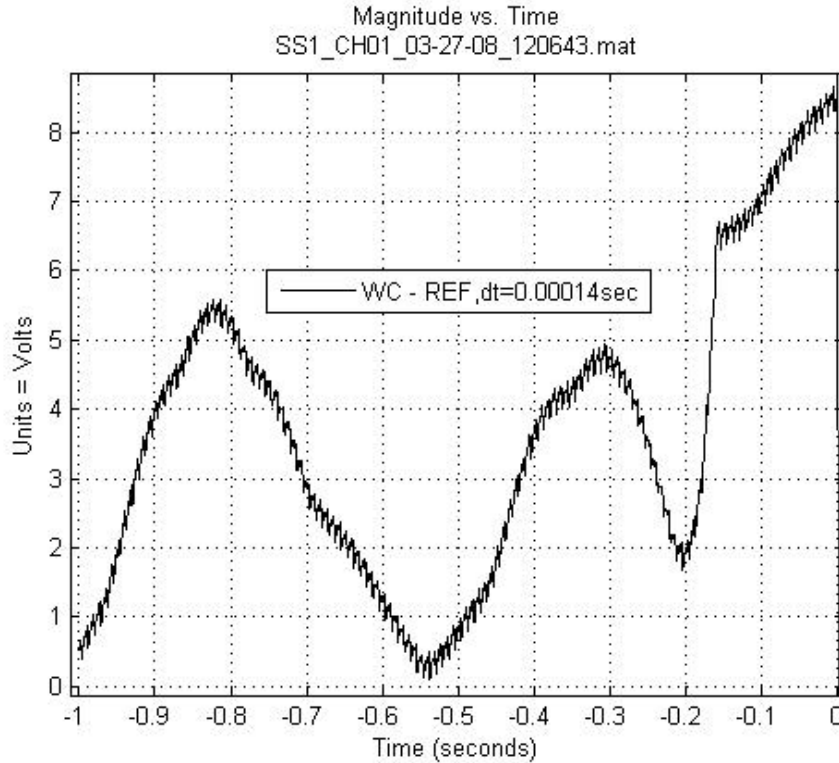


Fig. A4. WC-REF (Whole coil voltage, ref. to ground; 9V thresh) during 4A/s ramp, with quench detected long after start of development due to voltage limit. Large voltage swings are agree with dI/dt variations (Fig. A2) with 0.3H inductance.

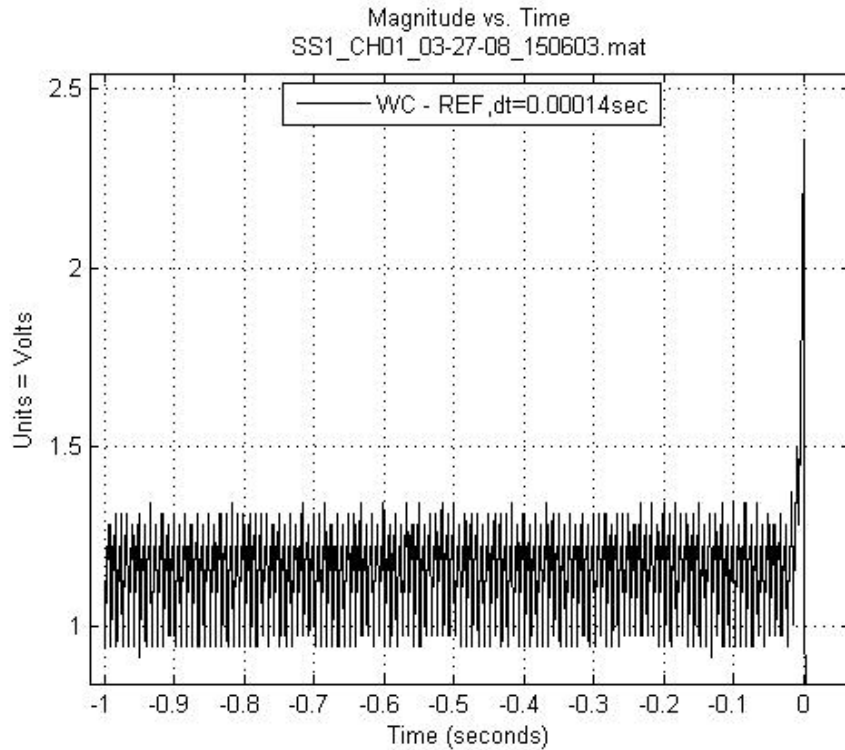


Figure A5. WC-REF voltage during 2A/s ramp generated by programmed current profile, illustrating no large voltage swings when profiles are used.

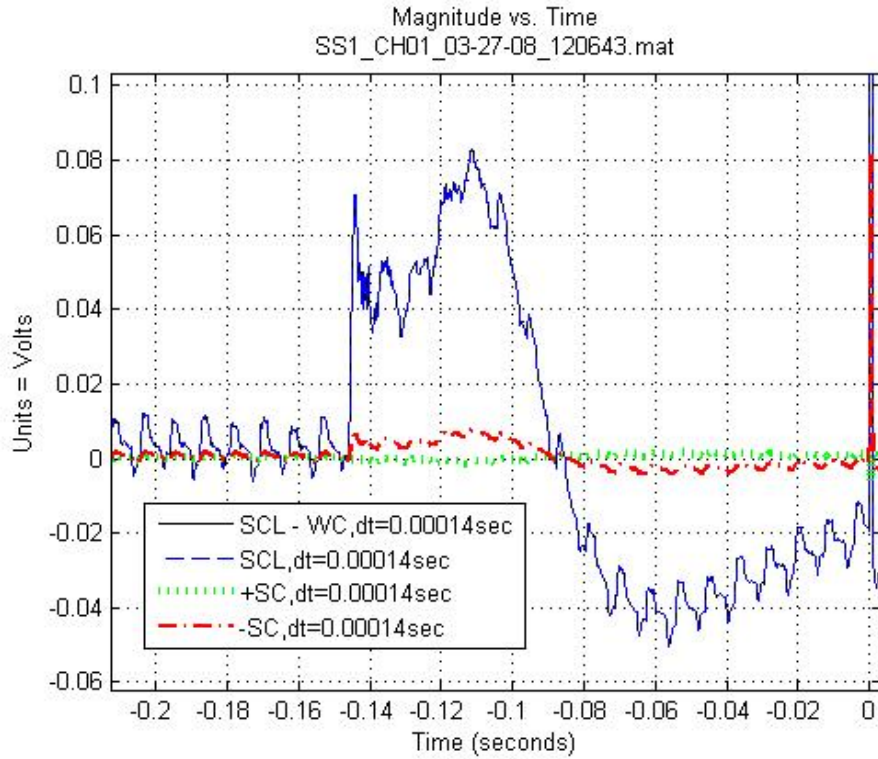


Fig. A6. Sc Lead signals during 4A/s quench event.

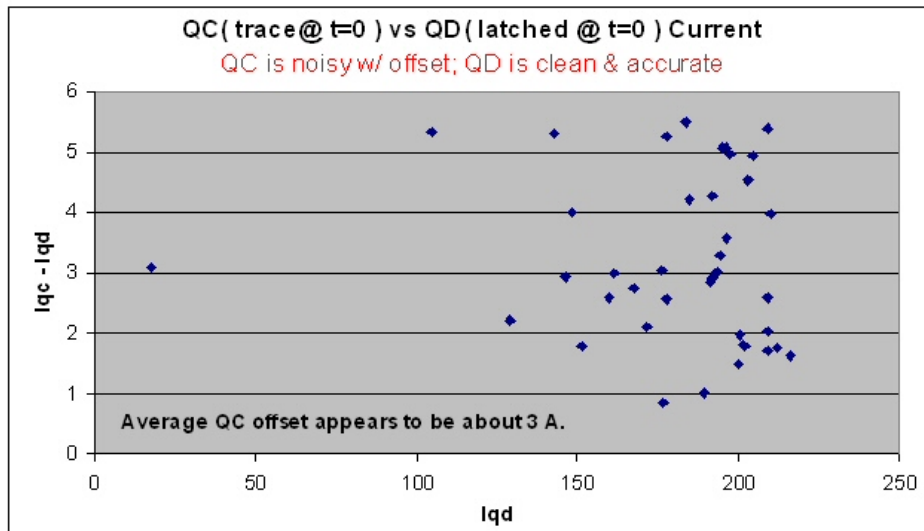


Fig. A7. Comparison of QC versus QD current values at quench detection time (t=0).